Autonomous Robots 11, 9–18, 2001

Vehicle Teleoperation Interfaces

TERRENCE FONG
The Robotics Institute, Carnegie Mellon University, Pittsburgh, Pennsylvania 15213, USA;
Institut de Systèmes Robotiques, Ecole Polytechnique Fédérale de Lausanne, CH-1015 Lausanne, Switzerland

CHARLES THORPE
The Robotics Institute, Carnegie Mellon University, Pittsburgh, Pennsylvania 15213, USA

Abstract. Despite advances in autonomy, there will always be a need for human involvement in vehicle teleoperation. In particular, tasks such as exploration, reconnaissance and surveillance will continue to require human supervision, if not guidance and direct control. Thus, it is critical that the operator interface be as efficient and as capable as possible. In this paper, we provide an overview of vehicle teleoperation and present a summary of interfaces currently in use.

Keywords: human robot interaction, mobile robots, remote driving, vehicle teleoperation, ROV, RPV, UAV, UGV

1. Introduction

1.1. Vehicle Teleoperation

Vehicle teleoperation means simply: *operating a vehicle at a distance* (Fig. 1). It is used for difficult to reach environments, to reduce mission cost, and to avoid loss of life. Although some restrict the term *teleoperation* to denote only direct control (i.e., no autonomy), we consider teleoperation to encompass the broader spectrum from manual to supervisory control. Furthermore, the type of control can vary and may be shared/traded between operator and vehicle.

Vehicle teleoperation has several characteristics which distinguish it from *remote control* (i.e., line-of-sight radio-based driving) and other types of teleoperation (e.g., telemanipulation). First, vehicle teleoperation demands reliable navigation. Since vehicles often are deployed in unknown or unstructured environments, navigation problems may lead to system-loss. Second, vehicle teleoperation requires efficient motion command generation. In many cases, task performance is directly correlated to how well a vehicle moves. Finally, vehicle teleoperation calls for localized sensor data. Because vehicles may cover large distances, map building and registration are significant issues.

1.2. Interfaces

In order for vehicle teleoperation to perform well, the human-robot interface must be as efficient and as capable as possible. All interfaces provide tools to perceive the remote environment, to make decisions, and to generate commands. Most interfaces also attempt to maximize information transfer while minimizing cognitive and sensorimotor workload. Finally, an interface may be designed to minimize training or to be user adaptive.

It should be noted that the importance of the operator interface does not diminish as level of autonomy increases. Even if a robot is capable of operating autonomously, it still needs to convey to the operator how and what it did during task execution. This is particularly important when the robot encounters problems or fails to complete a task. Thus, as robots become more-autonomous, interfaces are used less for control and more for monitoring and diagnosis.

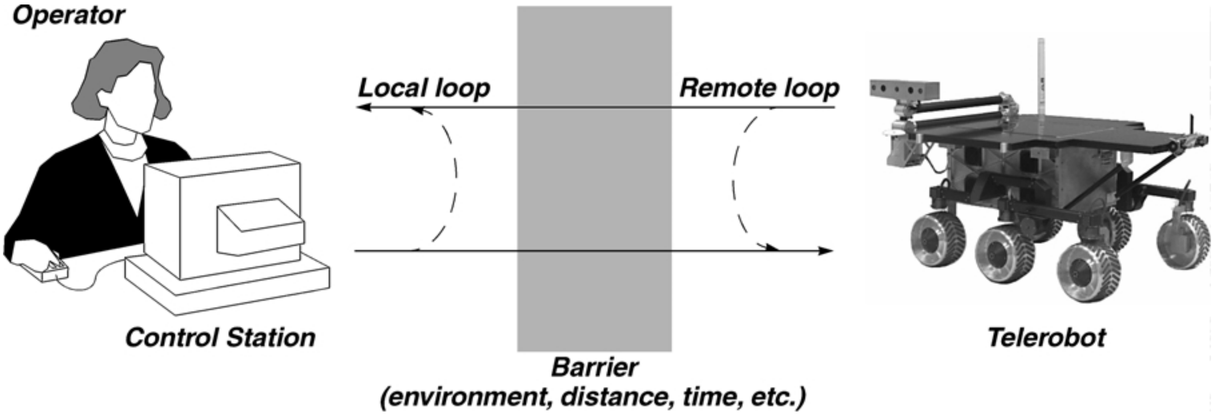

Figure 1. Vehicle teleoperation. An operator at a control station generates commands and receives feedback from displays. The remote vehicle executes the commands, often using some level of on-board autonomy.

2. History of Vehicle Teleoperation

Vehicle teleoperation first appeared in the early 1900's, but it was not until the 1970's that systems became widely used. Today, vehicle teleoperation is used for applications in the air, on the ground and underwater. Since development occurred over different periods and domains, it is not surprising that vehicle teleoperation is referred to by numerous terms (ROV, RPV, UAV, UGV). However, regardless of system type, many common characteristics and features exist.

2.1. Air Vehicles

Pilotless aircraft have existed since the early twentieth century (Jones, 1997). The first teleoperated air vehicles were drones, also called *Remotely Piloted Vehicles* (RPV), used for anti-aircraft training. Drones such as the US Army's RP-5 (1941) flew pre-programmed routes, although they were also occasionally piloted by radio control (Bailey, 1996). During the 1960's, NASA developed *Remotely Piloted Research Vehicles* (RPRV). In contrast to drones, which were small in general, RPRV's were full-size manned aircraft modified for remote controlled flight (Hallion, 1984).

Today, *Unmanned Air Vehicles* (UAV) are the most common teleoperated air vehicles. Modern UAV's are remotely piloted using radio or satellite links and are used for tasks such as reconaissance and target identification. Numerous UAV's have been used in combat, including the US Navy Pioneer and the US Air Force Predator (Fig. 2).

Figure 2. The Predator UAV carries a variety of sensors (EO, IR, SAR), and is flown by ground operators via radio or satellite links. It can autonomously execute flight plans once airborne. Left: predator (USAF Air Combat Command); right: predator control station (USAF Air Combat Command).

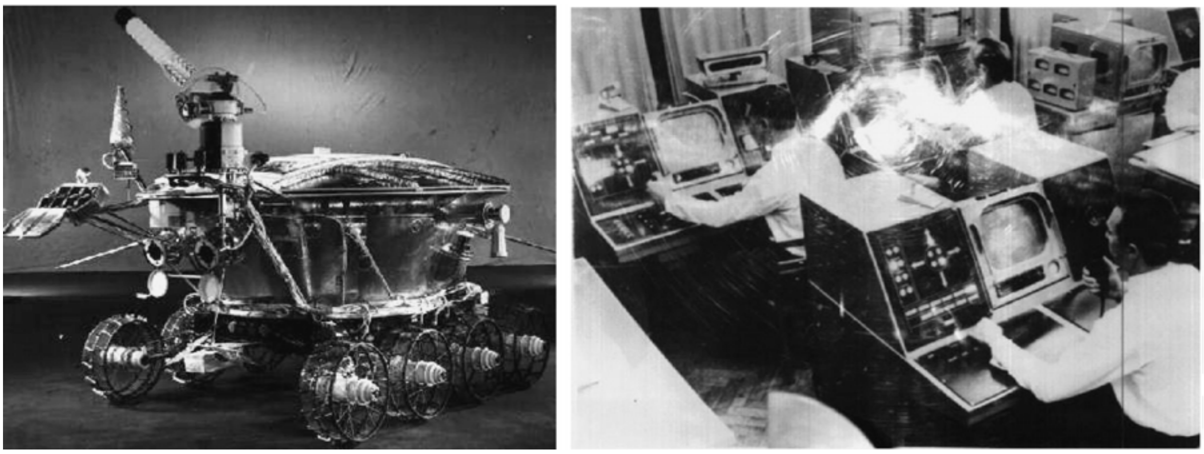

Figure 3. Lunokhod 1 operated on the moon for eleven months and covered 10,540 m. Left: Lunokhod 1 (Lavochkin); right: Lunokhod control station (NPO Lavochkina museum).

2.2. *Ground Vehicles*

We classify teleoperated ground vehicles into three categories: exploration rovers, *Unmanned Ground Vehicles* (UGV), and hazardous duty. Exploration rovers are ground vehicles designed to remotely perform science tasks such as *in-situ* sensing and sample collection. The first exploration rovers were the Soviet Lunokhods (Fig. 3) which explored the moon in the early 1970's (Carrier, 1992). Since then, NASA has produced numerous research vehicles (the Rocky series, Dante I/II, Nomad, etc.) and has landed the Sojourner rover on Mars.

UGV's are primarily used for tasks requiring remote navigation such as reconnaissance or surveillance. In the early 1980's, the Naval Ocean Systems Center developed the TeleOperated Dune Buggy and the TeleOperated Vehicle, both of which were driven with stereo video and replicated controls (Fig. 4). During the 1990's, the Tactical UGV program produced several vehicles which could be driven using either rate or waypoint-based control (Gage, 1996).

Hazardous duty vehicles work in conditions which pose extremely grave dangers (e.g., the vehicle may be destroyed by explosion). The first notable systems were the Remote Reconnaissance Vehicle and the Remote

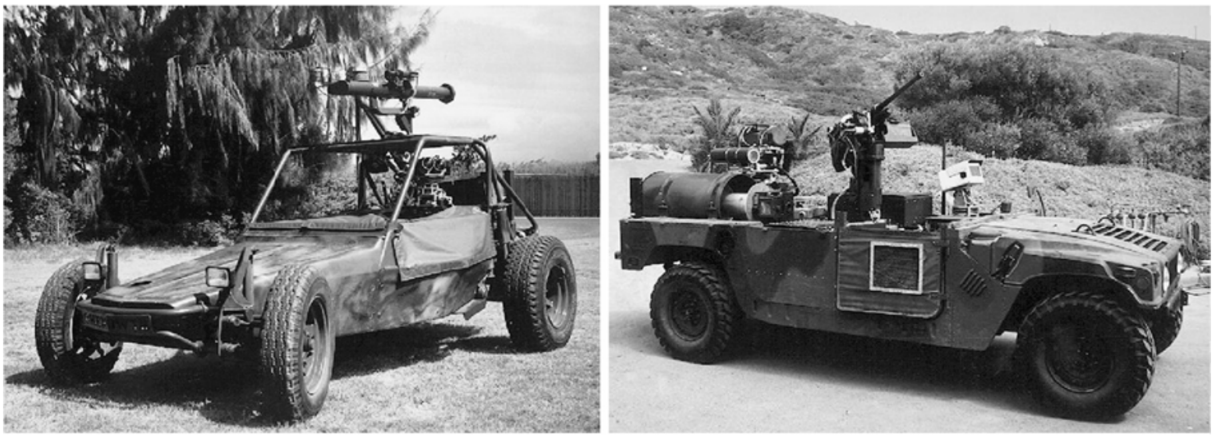

Figure 4. Unmanned Ground Vehicles. Left: TeleOperated Dune Buggy (SPAWAR Systems Center); right: TeleOperated Vehicle (SPAWAR Systems Center).

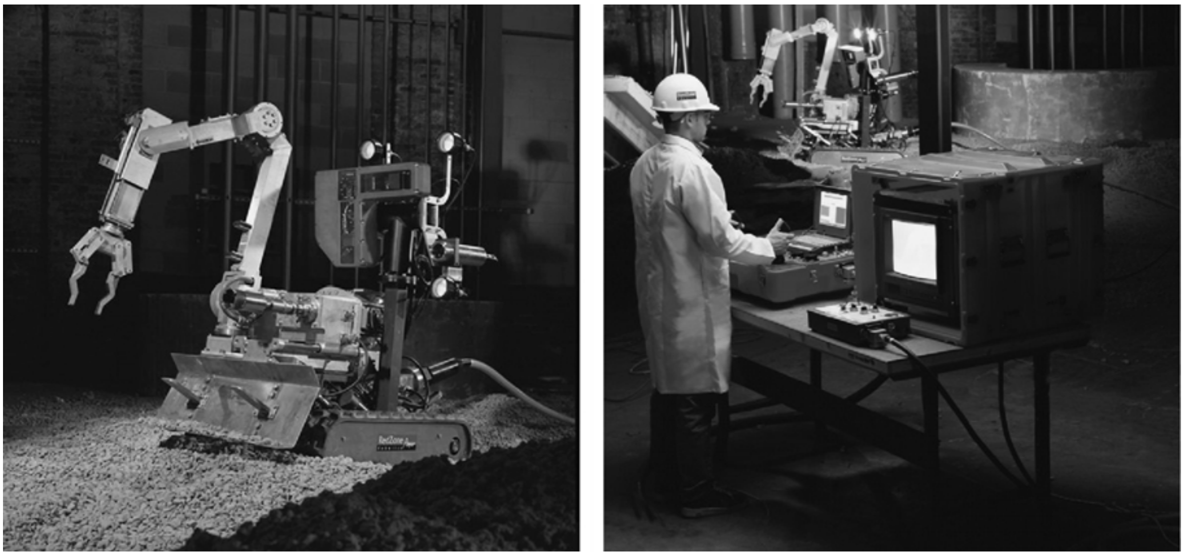

Figure 5. The Pioneer robot is designed to inspect and assess the Chernobyl nuclear reactor. Left: Pioneer robot (Carnegie Mellon University and RedZone Robotics, Inc.); right: Pioneer control station (Carnegie Mellon University and RedZone Robotics, Inc.).

Core Borer, which were used to explore and remediate the Three Mile Island reactor (Whittaker and Champeny, 1988). Recent hazardous duty applications include: mine rescue and survey (Hainsworth, 1993), bomb disposal (Graves, 1997), and assessment of the Chernobyl reactor (Fig. 5) (Blackmon et al., 1999).

2.3. *Underwater Vehicles*

Remotely Operated Vehicle (ROV)'s represent the largest market for vehicle teleoperation (Fig. 6). ROV's are unmanned submersibles which are generally tethered to a surface vessel. ROV's have existed since the early 1900's, but it was the success of the Cable Controlled Underwater Recovery Vehicle I (used by the US Navy in 1966 to recover an atomic bomb) and the subsea oil boom which spurred commercial development. Today, ROV's are used for a wide range of tasks (survey, inspection, oceanography, etc.) and have increasingly taken over roles once performed by manned submersibles and divers. Although most ROV's are controlled using joysticks and video monitors, some

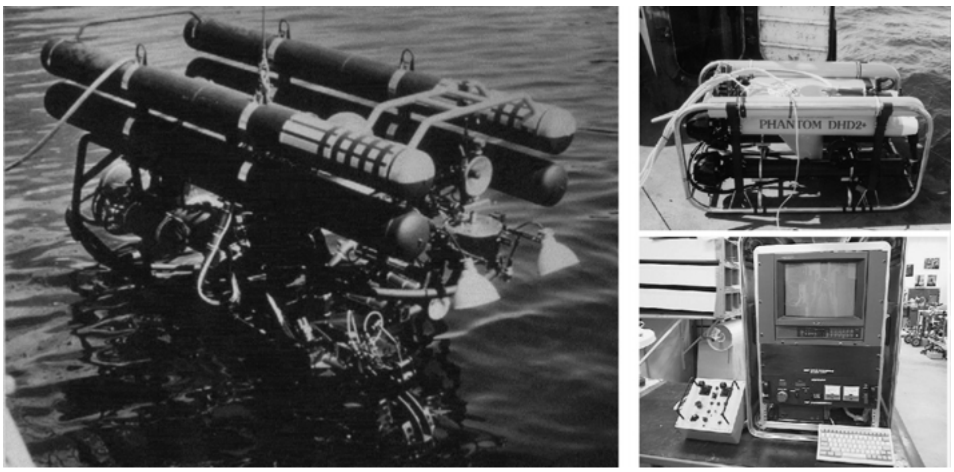

Figure 6. Remotely Operated Vehicles. Left: Cable-Controlled Underwater Recovery Vehicle I (SPAWAR Systems Center, San Diego); right: a commercial ROV used for undersea inspection and its control console.

recent systems incorporate autonomous functions such as station keeping and track following.

3. Vehicle Teleoperation Interfaces

We classify operator interfaces currently used for vehicle teleoperation into four categories: *direct*, *multimodal/multisensor*, *supervisory control*, and *novel*. Direct interfaces contain all "traditional" systems based on hand-controllers and video feedback. Multimodal/multisensor interfaces provide multiple control modes or use fused data displays (e.g., virtual reality). Supervisory control interfaces are designed for high-level command generation and monitoring. Novel interfaces use unconventional input methods or are intended for unusual applications.

3.1. Direct

The most common method for vehicle teleoperation has traditionally been the direct interface: the operator directs the vehicle via hand-controllers (e.g., 3-axis joysticks for vehicle rates) while watching video from vehicle mounted cameras (Fig. 7). This is often referred to as "inside-out" driving/piloting because the operator feels as if he is inside the vehicle and looking out. Recent direct interfaces include a system for tunnel and sewer reconnaissance (Laird et al., 2001), remote mine rescue (Hainsworth, 2001), and video-based telepresence for submersibles (Ballou, 2001).

Direct interfaces are appropriate when: (1) real-time human decision making or control is required and (2) the environment can support high-bandwidth, low-delay communications. Although direct interfaces can be used outside these conditions, the resulting performance is sub-optimal. In particular, direct control in the presence of delay (transmission or otherwise) is tedious, fatiguing, and error prone (Sheridan, 1992).

To minimize training, some direct interfaces provide controls which are spatially and functionally identical to those normally used for piloted vehicles. Many UAV's, for example, are flown using a ground cockpit which mimics the design and layout of aircraft cockpits (Canan, 1999). Other interfaces attempt to improve operator performance by providing a sense of telepresence via head-mounted video, binaural sound, and physical cues (Gage, 1996).

It is well known that direct interfaces can be problematic. A study conducted by McGovern (1990) found that loss of situational awareness, inaccurate attitude judgement, and failure to detect obstacles are common occurrences. Other researchers have studied sensorimotor requirements (Kress and Almaula, 1988) and the impact of video system design on remote driving (Glumm et al., 1992). Finally, since the operator is an integral part of the control loop and because he depends on video for perception, direct interfaces typically demand low-delay, high-bandwidth communications.

3.2. Multimodal/Multisensor

When a vehicle operates in a complex or highly dynamic situation, it may be difficult for the operator to

Figure 7. Direct teleoperation interface (International Submarine Engineering, Ltd.).

accurately perceive the remote environment or to make timely control decisions. Multimodal and multisensor interfaces can be used to cope with these problems by providing efficient command generation tools and rich information feedback.

Multimodal interfaces provide the operator with a variety of control modes (individual actuator, coordinated motion, etc.) and displays (text, visual, etc.). Multimodal interfaces are useful for applications which demand context specific actions, i.e., when it is necessary to select control modes and displays based on situational requirements (Fig. 8). Recent multimodal interfaces have been used for volcano exploration (Fong et al., 1995), satellite servicing (Lane et al., 2001), and to operate mobile robots having adjustable autonomy (Perzanowski et al., 2000).

Multisensor displays combine information from several sensors or data sources to present a single integrated view. In vehicle teleoperation, these displays can improve situational awareness, facilitate depth judgement, and speed decision making (Terrien et al., 2000). Draper and Ruff (2001) discuss the use of multisensor displays for improving Predator UAV operator performance. Nguyen et al. (2001) describe several virtual reality based interfaces for exploration, one of which is shown in Fig. 9. In contrast to direct interfaces, virtual reality provides an external perspective which allows the operator to drive/pilot the vehicle from the "outside".

3.3. Supervisory Control

The term *supervisory control* is derived from the analogy between a supervisor's interaction with subordinates (Sheridan, 1992). To effect supervisory control, the operator divides a problem into a sequence of subtasks which the robot then executes on its own. This means that the robot must have some level of autonomy: it must be capable of achieving goals (even limited ones) while keeping itself safe.

Supervisory control interfaces are designed for high-level command generation, monitoring & diagnosis. These interfaces are well suited for applications involving low-bandwidth or high delay communications. Cooper (1998) describes how earth-based operators used the *Rover Control Workstation* (Fig. 10) to control the Sojourner rover on Mars. Numerous image-based waypoint interfaces have been developed including Cameron et al. (1986) and Kay (1997).

In vehicle teleoperation, the operator's work is focused primarily on navigation and motion

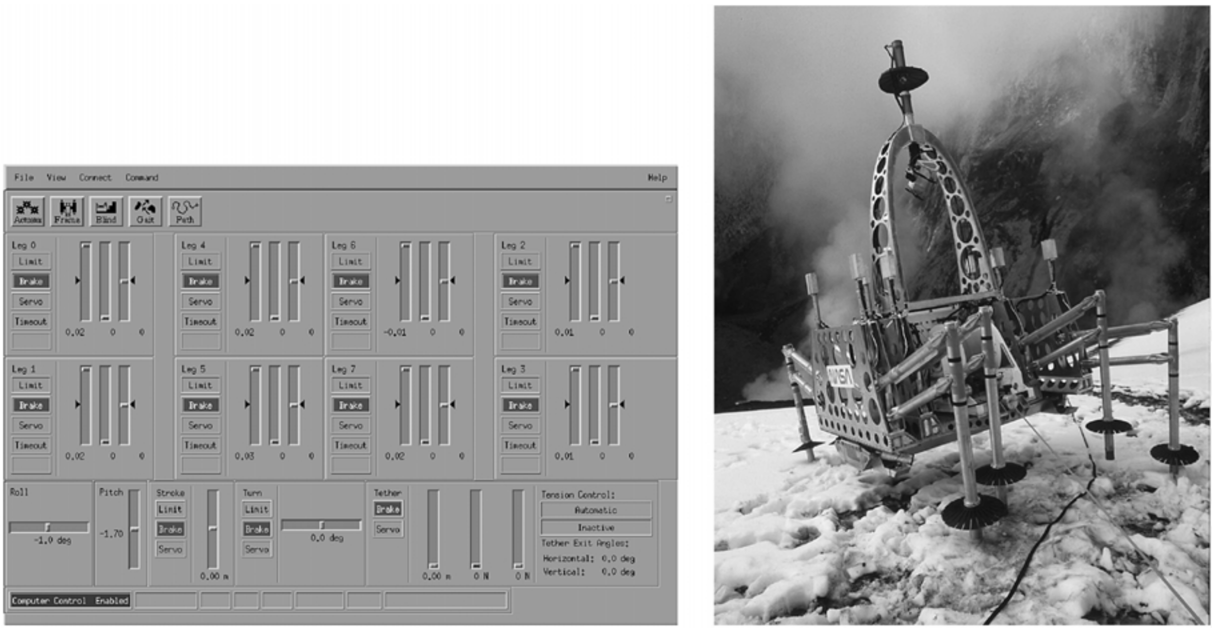

Figure 8. UI2D (Left) provided multiple control modes, ranging from individual actuator to path-based, for operating Dante II (right) in the Mt. Spurr, Alaska volcano (Carnegie Mellon University).

Figure 9. VIZ. This virtual reality based interface concisely displays numerous data sets: stereo-vision based terrain, digital elevation map, and simulated descent images (NASA Ames).

command generation. Thus, supervisory control interfaces provide tools to make these tasks easier (Fig. 10). Facilities for task planning and sequence generation (often supported by simulation and real-time visualization) are common. Additionally, interfaces often provide methods for reviewing results, so that the operator can monitor and identify execution anomalies.

There are many design challenges for supervisory control interfaces including display layout, managing human-robot interaction, and facilitating sharing/trading of control. For example, supervisory control interfaces must provide mechanisms for the operator and the robot to exchange information at different levels of detail or abstraction. This is particularly important when the robot has problems performing a task and the operator needs to ascertain what has happened.

3.4. Novel

The last category of vehicle teleoperation interfaces are the novel interfaces. Of course, the term "novel" is relative: many present-day interfaces (e.g., virtual reality systems) were once called "novel", but are now commonplace. Thus, it is possible, or perhaps likely, that the interfaces described below will cease to be novel at some point in the future.

Some interfaces are novel because they use unconventional input methods. Amai et al. (2001) describes a hands-free remote driving interface based on brainwave and muscle movement monitoring: beta-wave amplitude controls vehicle speed and gaze direction sets the heading. Fong et al. (2000) describe the *HapticDriver* (a haptic interface which enables "drive-by-feel") and the *GestureDriver* (a vision system which maps hand movements to motion commands).

Web-based interfaces (Fig. 11) are novel because they are a unique application of the WorldWideWeb. A Web interface is attractive because it can be accessed world-wide, is highly cost-effective, and requires little (or no) operator training. At the same time, however, Web-based teleoperation is susceptible to problems that more traditional systems do not have to deal with (e.g., communication bandwidth through the Internet varies significantly).

For some applications, installing conventional control stations is impractical (or impossible) due to

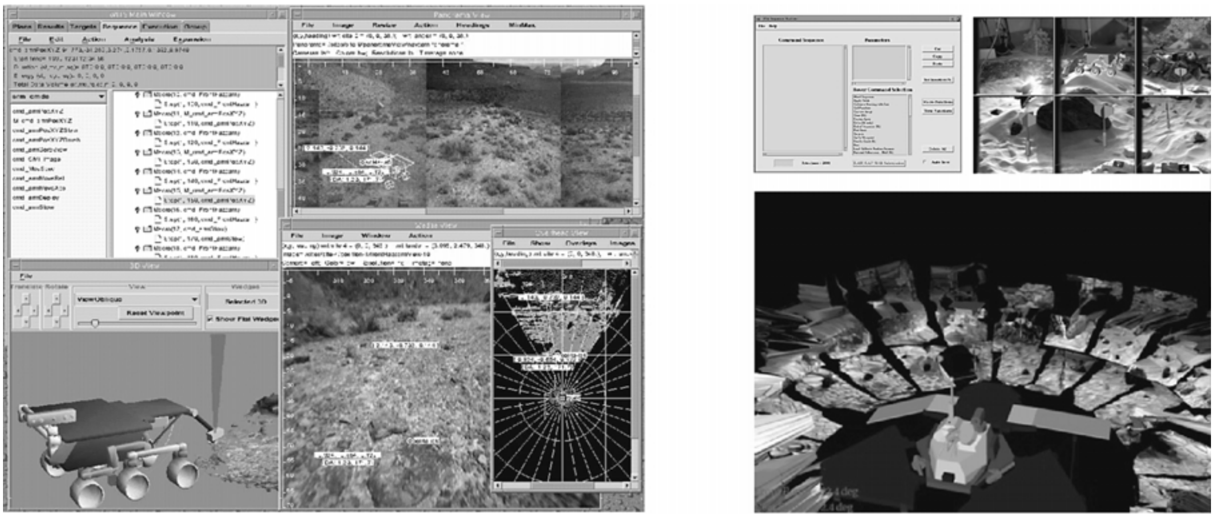

Figure 10. Supervisory control interfaces. Left: The Web Interface for TeleScience (WITS) provides numerous command and analysis tools (NASA JPL); right: The Rover Control Workstation (RCW) was used to operate Sojourner on Mars (NASA JPL).

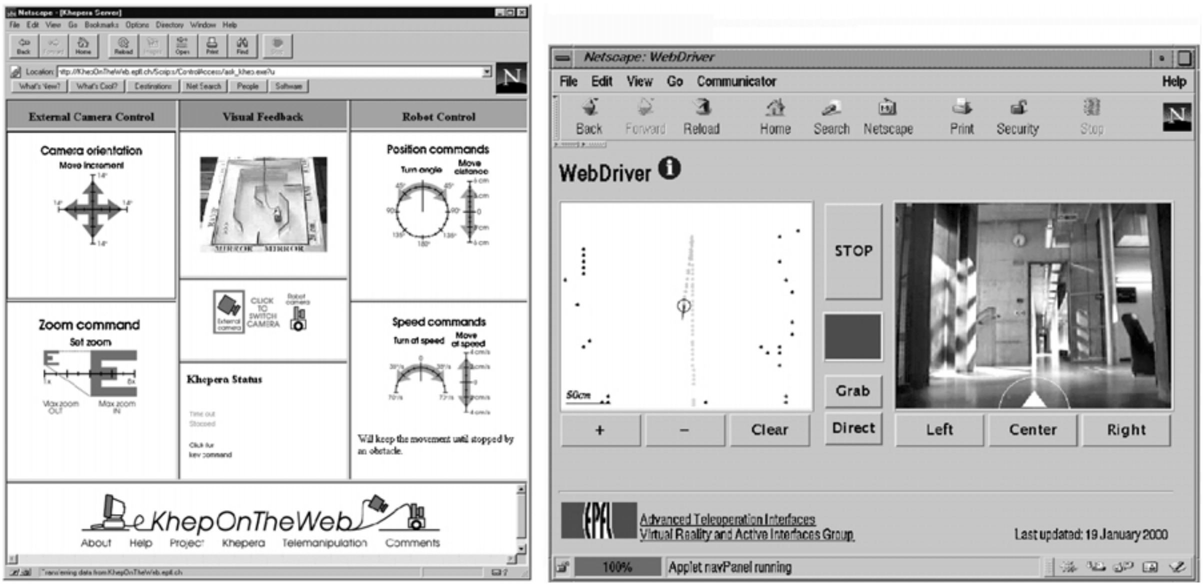

Figure 11. Web interfaces for remote driving (Swiss Federal Institute of Technology, Lausanne).

monetary, technical or other constraints. An alternative is to use a Personal Digital Assistant (PDA) as an interface devices. PDA's are lightweight, shirt-pocket portable, and have touch-sensitive displays. PDA interfaces for remote driving are described in Fong et al. (2000) and Perzanowski et al. (2000). One of these interfaces, the *PdaDriver,* is shown in Fig. 12.

Lastly, novel interfaces are not just characterized by unconventional input methods or displays. Interfaces are also novel if they are used in unusual ways. Paulos and Canny (2001) describe a system which enables operators to "project their presence into a real remote space". In other words, the teleoperated vehicle serves as a fully-mobile, physical proxy (a "real-world avatar") for the operator.

Figure 12. PdaDriver is a Personal Digital Assistant based interface for remote driving (Carnegie Mellon University and Swiss Federal Institute of Technology, Lausanne).

4. Conclusion

Vehicle teleoperation has become increasingly important for a wide range of applications in the air, on the ground, and underwater. Vehicle teleoperation interfaces provide tools and displays to perceive the remote environment, to make decisions, and to generate commands. Rate control interfaces are widely used in domains which can support high-bandwidth, low-delay communications. Multimodal/multisensor displays are increasingly being employed, especially for controlling vehicles in complex environments. Supervisory control interfaces, though currently few in number, will become more common as the use of autonomy increases, particularly for low-bandwidth, high-delay applications.

Acknowledgments

We would like to thank the participants of the *Vehicle Teleoperation Interfaces* workshop (IEEE International Conference on Robotics and Automation, San Francisco, CA, April 2000) for their insightful presentations and for inspiring this paper. This work was partially supported by a grant from SAIC, Inc. and by the DARPA ITO MARS program.

References

Amai, W., Fahrenholtz, J., and Leger, C. 2001. Hands-free operation of a small mobile robot. *Autonomous Robots*, 11(1):67–73.

Bailey, B. 1996. Drones in southeast Asia. *55th Strategic Reconnaissance Wing Association*, Inc., Navarre, FL.

Ballou, P. 2001. Improving pilot dexterity with a telepresent ROV. In *Proceedings of the Vehicle Teleoperation Interfaces Workshop, IEEE ICRA*, San Francisco, CA.

Blackmon, T., Nguyen, L., Neveu, C., Rasmussen, D. et al. 1999. Virtual reality mapping system for Chernobyl accident site assessment. In *Proceedings of SPIE*, San Jose, CA, Vol. 3644.

Cameron, J. et al. 1986. Fusing global navigation with computer-aided remote driving of robotic vehicles. In *Proceedings of SPIE Mobile Robots*, Cambridge, MA.

Canan, J. 1999. Seeing more, and risking less, with UAV's. *Aerospace America*, 37(10):26.

Carrier, D. 1992. Soviet rover systems. In *Proceedings of the AIAA Space Programs and Technologies Conference*, Huntsville, AL.

Cooper, B. 1998. Driving on the surface of Mars using the Rover Control Workstation. In *Proceedings of SpaceOps 1998*, Tokyo, Japan.

Draper, M. and Ruff, H. 2001. Multi-sensory displays and visualization techniques supporting the control of unmanned air vehicles. In *Proceedings of the Vehicle Teleoperation Interfaces Workshop, IEEE ICRA*, San Francisco, CA.

Fong, T., Pangels, H., Wettergreen, D., Nygren, E., Hine, B., Hontalas, P., and Fedor, C. 1995. Operator interfaces and network-based participation for Dante II. In *Proceedings of the SAE 25th ICES*, San Diego, CA.

Fong, T., Conti, F., Grange, S., and Baur, C. 2000. Novel interfaces for remote driving: Gesture, haptic, PDA. In *Proceedings of SPIE Telemanipulator and Telepresence Technologies VII*, Boston, MA.

Gage, D. 1995. UGV history 101: A brief history of Unmanned Ground Vehicle (UGV) development efforts. *Unmanned Systems Magazine*, 13(3):9–16.

Glumm, M., Glumm, M., Kilduff, P., and Masley, A. 1992. A study on the effects of lens focal length on remote driver performance. Army Research Laboratory, Technical Report ARL-TR-25.

Graves, A. 1997. Enhancement of a direct control teleoperator system. Centre for Computational Intelligence, De Montfort University, Leicester, UK, Working Paper 1.

Hainsworth, D. 1993. Mine emergency survey vehicle: Numbat. In *Proceedings of the 25th International Conference of Safety in Mines Research Institutes*, Pretoria, South Africa.

Hainsworth, D. 2001. Teleoperation user interfaces for mining robotics. *Autonomous Robots* 11(1):19–28.

Jones, C. 1997. Unmanned aerial vehicles (UAVS). An assessment of historical operations andfuture possibilities. Air Command and Staff College.

Kay, J. 1997. STRIPE: Remote driving using limited image data. Ph.D. Thesis CMU-CS-97-100, Carnegie Mellon University, Pittsburgh, PA.

Kress, G. and Almaula, H. 1988. Sensorimotor requirements for teleoperation. FMC Corporation, San Diego, CA, Report R-6279.

Laird, R. et al. 2001. Issues in vehicle teleoperation for tunnel and sewer reconnaissance. In *Proc. of the Vehicle Teleoperations Interfaces Workshop*, IEEE ICRA, San Francisco, CA.

Lane, C. et al. 2001. Advanced operator interface design for complex space telerobots. *Autonomous Robots*, 11(1):49–58.

McGovern, D. 1990. Experiences and results in teleoperation of land vehicles. Sandia National Laboratories, Albuquerque, NM, Technical Report SAND 90-0299.

Nguyen, L. et al. 2001. Virtual reality interfaces for visualization and control of remote vehicles. *Autonomous Robots*, 11(1):59–66.

Paulos, E. and Canny, J. 2001. Designing personal tele-embodiment. *Autonomous Robots*, 11(1):85–93.

Perzanowski, D. et al. 2000. Towards seamless integration in a multimodal interface. In *Proceedings of AAAI WIRE*, Pittsburgh, PA.

Sheridan, T. 1992. *Telerobotics, Automation, and Human Supervisory Control*, MIT Press: Cambridge, MA.

Terrien, G., Fong, T., Thorpe, C., and Baur, C. 2000. Remote driving with a multisensor user interface. In *Proceedings of SAE ICES*, Toulouse, France.

Whittaker, W. and Champeny, L. 1988. Conception and development of two mobile teleoperated systems for TMI-2. In *Proceedings of the International Meeting and Topical Meeting TMI-2 Accident*, American Nuclear Society.

Terry Fong received his B.S. (1988) and M.S. (1990) in Aeronautics and Astronautics from the Massachusetts Institute of Technology. From 1990 to 1994, he was a computer scientist in the NASA Ames Intelligent Mechanisms Group and was co-investigator for virtual environment teleoperation experiments involving wheeled, free-flying and walking mobile robots. He is currently pursuing a Robotics Ph.D. at CMU and is performing his thesis research on advanced teleoperation interfaces at EPFL. His research interests include human-robot interaction, Web-based interfaces, and field mobile robots.

Charles Thorpe is Principal Research Scientist at the Robotics Institute of Carnegie Mellon University. He received his Ph.D. in Computer Science from Carnegie Mellon University (1984) under the guidance of Raj Reddy. He has published over 120 peer-reviewed papers in mobile robotics, computer vision, perception, teleoperation, man-machine interfaces, and intelligent highway systems. He is the leader of the Navlab group, which is building computer-controlled cars and trucks. His research interests include computer vision, planning, and control of robot vehicles operating in unstructured outdoor environments.